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MASS AND LEVEL GAGING
FOR LIQUID HYDROGEN TANKS

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ABSTRACT (NASA TMX-50307)

Accurate gaging of the amount of propellants in rocket tanks is often necessary if high performance and mission reliability is to be obtained for rocket systems. Gaging of propellants in vehicle tanks is required for proper filling and propellant utilization. Quantity gaging is also required for ground storage and research purposes. Gaging devices for common rocket propellants have been developed to a fairly high state of reliability and accuracy. However, with the use of liquid hydrogen as a propellant, new gaging problems which stem from hydrogen's unique properties have arisen.

A study has been conducted at the Lewis Research Center to evaluate various devices and techniques for gaging liquid hydrogen. The techniques studied included: capacitance, pressure head, bouyant force, radiation, and sonar gages; weighing; floats; ultrasonic switch; "hot" wire; and temperature rake. All the devices were analyzed and some of the sensors were tested in liquid hydrogen to gain experience in their operation and problems.

The study showed that most gaging devices could be classified into two major groups: continuous-reading total-content sensors and

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point sensors. Each group has a principal source of error: the mass of gas for the total-content sensors and sampling errors for the point sensors. The sensors in each group have essentially the same inaccuracy arising from the main error source of that group. The study also revealed that of the sensors considered, the "hot" wire point sensor was best for tank filling. Sensors based on the nuclear radiation and sonar techniques considered showed relatively little promise at this time for practical reasons. The float showed promise although its applications are limited.

INTRODUCTION

Upper stages of advanced chemical rockets such as the Saturn, Apollo, and Nova as well as nuclear rockets will be using liquid hydrogen as a propellant. As for earlier vehicles, there will be a need for liquid level gaging of this fluid.

Generally, liquid level sensors are used to determine the liquid mass or head in tank filling, holding, and propellant utilization systems, and also in inventory and research applications. The latter two applications are so varied that they will not be described further. Tank filling and holding to a predetermined liquid mass requires a flow control system which is controlled by a "liquid level" sensor. The sensor may be a continuous reading type or a rake of point sensors which is located in the vicinity of the required level. Propellant utilization systems control the relative flows of the liquid propellants so that no propellant, ideally, is left over at burnout. A "liquid level" sensing and control system monitors the liquid mass in each tank during

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outflow and corrects the relative propellant flows to obtain the desired result. The level sensor may be either a continuous sensor or a rake of point sensors.

Although some information on level gaging exists (ref. 1-4), little information on liquid level gaging for hydrogen is available. Thus, a program was set up to study analytically and experimentally a number of common types and principles of liquid level sensors for hydrogen applications. The analytical study stresses the effect of tank conditions upon level sensing accuracy. Specific commercial designs and electronics are not, in the main, compared in this paper. Testing of specific commercially available level sensors is being performed by the cryogenic engineering laboratory of the National Bureau of Standards under an NASA contract.

This paper will describe the results of the NASA study which was based primarily on qualitative considerations in conjunction with some quantitative analysis and experience gained by the author from limited testing of commercial designs. Sensors will be classified according to the way they use the normally large difference in properties between the gas and liquid phase in determining the liquid mass contained in a tank and also according to the type of data output. Following this discussion, the operating principles of the sensors considered will be described. The factors which affect level gaging accuracy and sensor practicality are then discussed after typical tank conditions during filling and propellant utilization operations are described. Finally, evaluation of sensors is made based on error sources, practicality, and

application (filling, propellant utilization, and zero-gravity operation) both for sensor types within the same class and for the different classes of sensors.

DESCRIPTION OF LIQUID LEVEL SENSORS

General Classification

There are many methods by which the liquid mass contained in a tank might be gaged. All of them depend upon the normally large difference of some property across the interface between the liquid and the gas above it (e.g., liquid density is normally much greater than gas density). Some level sensors, called total-content sensors, measure directly or indirectly the total mass of fluid in the tank. Others, called point sensors, use the large property difference across the interface directly to trigger an electronic circuit and thus locate the interface. Another group is able to "follow" the interface because of this property difference.

It is possible to also classify sensors according to their type of output data. Many give continuous "level" readings while the point sensors give and off-on (when in liquid or in gas) type of output. The continuous reading gages are single sensors that sample the "level" along the length of the tank. Usually a number of point reading sensors placed at different levels in the form of a rake are required to determine the liquid mass. The continuous reading sensors continuously monitor the mass contained while the point sensor rake gives point indications of the interface location as it passes a sensor. Filling and propellant

utilization systems can use either scheme. For the purposes of classification, then, sensor types will be cataloged as:

1. Continuous-reading, total-content sensors.
2. Continuous-reading, interface-following sensors.
3. Point sensors.
4. Miscellaneous sensors.

A brief description of the sensors considered will now be given on the basis of the above mentioned classification scheme. Each type of sensor will be described briefly with the aid of a schematic drawing of the principle of operation. The approximate equation of operation--that is, the equation that relates the principal properties to the output signal for each sensor--is included for reference in Appendix B. However, no derivation or description of the equations is given due to the lack of space. The symbols used in the equations are described in the nomenclature (Appendix A).

Continuous-Reading, Total-Content Sensors

Pressure head (strain element or manometer type). - A differential pressure transducer has its ports connected to the top and bottom of the tank (fig. 1a) such that the pressure difference acting on it is essentially the total head of fluid (gas and liquid) in the tank. Another scheme would be to replace the transducer by a column of another liquid which would then act as a manometer (fig. 1b). The level of this easier-to-gage liquid is then measured to determine the head of the fluid in the tank. Thus, a continuous reading of head, and consequently mass, is obtained for a given tank configuration.

Capacitance. - The plates of a capacitor (fig. 2) running the length of the tank are partly immersed in the liquid contained in the tank. The fluid in the tank acts as the dielectric for the capacitor. As the level changes, the capacitance changes because the dielectric constant of the liquid is normally different than that of the vapor. Again, this device continuously measures the total mass in the tank.

Bouyant force. - A non-floating bob is hung from a scale and immersed in the liquid (fig. 3). As the level rises, the apparent weight of the bob, as measured by the scale, decreases as more of the bob is submerged because of the added bouyant force. Thus, the weight of the fluid in the tank can be continuously determined.

Weighing. - Here the entire tank is supported by a scale arrangement (fig. 4), and one observes the difference between the reading and the tank-empty reading as the liquid level changes. This difference will be the fluid weight on board.

Radiation. - For one possible scheme, a beam of gamma rays is aimed toward a gamma detector (ionization chamber) at the top of the tank (fig. 5). The amount of gamma radiation reaching the detector will depend on the amount scattered from the beam and therefore on the total mass of fluid through which the beam travels. A continuous indication of the contained mass can result.

Continuous-Reading, Interface-Following Sensors

Float. - A float will follow the interface because of the density difference across the interface. It now remains to sense the position of the float to provide a continuous reading of liquid height and

therefore liquid mass. One method is to have the float guided by vertical resistive wires which are part of a potentiometer circuit (fig. 6).

Sonar. - For sensors employing sonar, a sound impulse is generally directed upward through the liquid from a transducer, such as a piezo-electric crystal, at the bottom of the tank (fig. 7). This impulse bounces off the interface because of the large property (density times speed of sound) difference across the interface and is picked up again by the transmitting transducer. The total time of travel is electronically measured and gives the liquid head when multiplied by the speed of sound in the fluid.

Point-Reading Sensors

Critical valued "nulled" continuous sensor. - One means of getting point data is to connect the output of a continuous-reading sensor to a bridge circuit which is nulled for a particular level. Therefore, when the null point is reached, the particular level is located. For some applications, a number of nulls are programmed into the electronics to give digital level data.

Critical valued "shortened" continuous sensor. - If the length of a continuous gage is physically shortened, the sensor can be made to locate the interface since that is where the greatest property change takes place. Thus a point sensor results. Usually, this type of sensor is a shortened capacitor or a float switch.

Ultrasonic switch. - This sensor is effectively a vibrating spring-mass system which is driven to oscillate by electromechanical means (fig. 8).

Its electromechanical circuit is normally tuned to near resonance in gas. When the sensor contacts liquid, its motion is damped. The resulting change in electrical impedance or potential can actuate a relay, thus locating the interface.

"Hot" wire. - An electrically heated wire will be much warmer when surrounded by gas than by liquid due to the large difference in the coefficient of heat transfer between the wire and the two phases. The resistance of the wire will then be different when in the gas compared to when it is in the liquid. This change can be used to operate a relay and allow electronic sensing of the interface. A schematic of a "hot" wire point sensor is shown in figure 9.

Miscellaneous - Temperature Rake

In essence the temperature rake consists of a group of point temperature sensors. The interface location is determined by plotting the resulting temperature profile and locating the interface at that level which coincides with the saturation temperature. With this information, it is possible to obtain the liquid mass from a density profile which can be determined from the temperature profile and tank pressure.

COMPARISON OF SENSORS

Evaluating Factors

Evaluation of the various sensors considered will be based on several considerations such as the effect of tank conditions on accuracy, practicality, and applicability to the various requirements of interest in liquid hydrogen use. These evaluating factors will now be discussed.

Any deviation from the correct amount of liquid mass contained in a tank should be considered an error, since only propellant in the liquid form is generally of use in rocket systems. There are many factors which will affect the accuracy of a liquid level sensor. Further, these factors will affect one type of sensor more than another. Accuracies of the order of 0.1 percent of full scale seem to be desired for typical rocket propellant utilization and filling systems.

One source of inaccuracy is the error due to the mass of gas which will occur in the reading of all gages which sense the total mass contained in a tank. Another major source of inaccuracy is the sampling error which occurs in those sensors that do not sample the entire liquid mass. Some examples of sampling error sources are: waves, splashing, tank distortion, boiling and non-uniform boiling, density gradients, and uncertain sensor dimensions. The gravity field or vehicle acceleration will also effect some sensors' accuracy. (the case of zero gravity is a special case of this problem and will be discussed later). The time lag error that results by slow sensor cooldown during a filling operation is also considered.

The practicality of the sensor must be considered in its evaluation. Practicality, as it is used herein, is a catch-all term for various effects such as: state-of-the-art; weight of system; inherent electrical problems; effect of fluid contamination; ease of servicing and check-out; shaping; safety to personnel; direct effect of flow on reading; effect of vibration on reading; flexibility of missions; filling applicability; and flight applicability. Finally, applicability for the

particular use or tank condition such as filling and holding, propellant utilization, and zero-gravity is considered.

Before these factors are discussed separately, it is desirable to describe typical tank conditions which occur during the filling and propellant utilization (PU) operations.

Tank Conditions

Filling and holding. - Normally a tank is filled on the ground (a well known steady gravity field) with the tank vented to atmosphere. Liquid is forced into the initially warm tank through initially warm piping. Much liquid, then, will gasify in the pipes causing fluid to enter the tank at a high velocity. A great deal of turbulence and splashing will normally occur in the tank because of this high velocity entering jet. The tank walls will normally be largely cooled by the time liquid begins to collect at the bottom. As the level rises, the turbulence will subside some, with the greatest decrease occurring when the fill inlet is submerged. Even when the tank is almost filled, there will still be a great deal of turbulence, waves, and boiling, although not nearly as severe as it was initially. These hydrodynamic disturbances, of course, represent sources of a considerable sampling error. Although the tank walls will be largely cooled before liquid strikes them, most liquid level sensors are heavy with inadequate surface area and consequently will cool down much more slowly. When the liquid strikes these sensors, they will cool by film boiling, which will greatly retard

proper phase indication until the sensor has cooled to nearly the temperature of the liquid.

During holding, liquid is added to the tank to compensate for that which boils off. Generally, the liquid is in a turbulent state although not as violent as in the filling case. Therefore, holding is similar to, but less severe than, the filling situation.

Propellant utilization. - During operation of the propellant utilization system, there will be outflow from the tanks under a varying gravity field. Sloshing and splashing, set up by the motion of the rocket, will result in a non-placid interface. The tanks will normally be pressurized to strengthen the tank structure and provide for outflow or to prevent pump cavitation. Pressurization and heat leak in a gravity field allows time-varying temperature and property gradients to form in the liquid and gas volumes. All the above factors can constitute sources of error for the propellant utilization sensing system. Should the tank not be pressurized sufficiently to stop boiling, which would be the case when using a boiling liquid pump, then errors are possible due to uncertain liquid density caused by the bubbles in the liquid volume.

Comparison can now be made among the various sensors considered according to the effect of error sources (mass of gas, sampling errors, and gravity) on accuracy and the practicality of the sensor. Where possible, similar performance characteristics will be pointed out.

Continuous-Reading Total-Content Sensors

Mass of gas. - The continuous-reading total-content level sensors (e.g., pressure head) sense the sum of the liquid mass and mass of gas. Since only the measurement of liquid mass is desired, the contribution of the mass of gas represents an error which will increase with increasing tank pressure or decreasing gas temperature and liquid level.

It can be shown that all continuous total-content gages exhibit nearly the same error due to the mass of gas if they are all calibrated and used similarly in hydrogen. For calibration with the tank initially filled with saturated hydrogen vapor at atmospheric pressure, the error can be given approximately by the relation¹

$$\eta_{FS} \approx \frac{\bar{\rho}_g \left(\frac{L-h}{L} \right) - \bar{\rho}_{g, Cal}}{\bar{\rho}_l - \bar{\rho}_{g, Cal}}$$

where the bar refers to spatial averages. Calculated variations of error are shown in figure 10 for several average gas weight densities. Therefore, at least in theory, there is no advantage of one continuous total-content sensor over another when considering the error caused by the mass of gas.

Gravity error. - The fluid in a propellant tank may be influenced by gravity fields ranging from zero to greater than one gravity. Many sensors do not read mass, but rather read weight directly. Therefore their readings are subject to the varying acceleration of the rocket.

¹ This error equation applies to all total content sensors, except the capacitor, when used in other cryogenic fluids.

Of those continuous total-content sensors considered, only the capacitance and radiation gages are true mass gages and are, therefore, independent of gravity. The pressure head manometer type gage cancels out the gravity term and can therefore be used in varying acceleration fields. In zero gravity only the true mass gages could give meaningful readings. In addition, zero gravity presents a special problem because of uncertain fluid boundaries and liquid cohesion to the sensor elements. This will be discussed further in a later section on applications.

Sampling error. - Most "liquid level" gages sense the liquid mass locally. This local reading may not be indicative of the total liquid mass contained, resulting in a sampling error. Probable sampling errors with their source are listed below:

1. Interfacial sampling errors. - Basically, the source of these errors are waves, which cause fluctuations in the reading of the locally sampling sensor. Sources of these sampling errors are: sloshing, turbulence caused by outflow, and boiling.

2. Fluid volume density sampling errors. - These errors are caused by the variation of the average density sampled locally by the sensor compared to the true whole-tank average density. Some examples are described below:

- a. Density gradients. - These form in the vertical and radial directions during tank pressurization.

- b. Spatially non-uniform boiling. - This occurs when an internal sensor cools by boiling heat transfer. In this case the

average fluid density surrounding the probe could be much less than the tank average. This is very important during a filling operation.

c. Uniform boiling. - Uniform boiling must be considered because it raises the liquid level as it lowers the bulk liquid density.

d. Splashing. - Splashing similarly effects the gas volume in that it raises the average density in the gas, and more important, splashed drops contact and adhere to the sensor causing a possible error.

3. Sensor and tank distortion. - Tank pressure and fluid temperature changes can change tank and/or sensor dimensions and location thus affecting the accuracy of many sensors.

The relative effect of these internal sampling errors on instrument accuracy is portrayed in Table I².

Weighing by nature is not sensitive to any of the internal sampling errors mentioned in the previous paragraph, but rather has its own set of sampling errors which are external to the tank. Some examples are: snow, ice, and liquid air formation on the tank walls; umbilicals; and wind and rain forces.

Practicality. - Perhaps the most efficient way to handle this factor is to compare the total-content sensors in a self-explanatory chart (Table II) on the basis of the various practicality items previously listed. Pertinent remarks are also included in the table for further clarification.

² The letter grades in all tables are not to be considered as absolute values. They are meaningful only in the relative comparison of sensors for a particular item.

Continuous-Reading Interface Followers

A departure from the format used in the previous discussion is required for this class of sensors. Neither the sonar technique nor the float will require a detailed discussion of errors since there are certain overriding characteristics to be considered.

Both sensors are only slightly affected by mass of gas errors except near the thermodynamic critical point. When thermodynamic critical point is approached, neither sensor can follow the interface. This happens because the property difference at the interface that they rely on for operation disappears at this condition. Neither device is affected by the gravity field as such.

The previous paragraph discussed similarities in sensor behavior; important differences exist, however. It is therefore better to now discuss the sensors separately.

Sonar. - To date a continuous reading sonar level sensor for liquid hydrogen has not been developed because the sound impulse returning to the transducer has not been of sufficient magnitude to operate the timing circuit. This occurs because of any or all of the reasons stated below.

1. The dispersion of sound energy is normally high and is intensified by bubbles in the liquid and/or a rough interface.
2. It is difficult to match the impedance of the sound transducer to liquid hydrogen.
3. The sound transducer is generally a piezoelectric crystal, which may lose its piezoelectric quality at hydrogen temperature.

Float. - A float must be a sealed volume since a vented one may fill up and sink because of internal condensation and/or the usual problems of a "boat on a rough sea." It is difficult to build a sealed float strong enough to withstand high external pressure and still float in liquid hydrogen. The maximum pressure that a sealed spherical aluminum float can stand as a function of float radius and "carry" weight for a practical design safety factor of 3 is illustrated in figure 11. The figure shows that the maximum allowable pressure is limited by the volume fraction submerged which should be about $\xi = .5$ for best accuracy. Furthermore, any load carried by the float (W_c) will dictate a relatively large minimum float size. The float, being necessarily large, will average out much of the interface disturbances. Also a continuous reading float will be pre-cooled by the liquid at the beginning of its travel. Unfortunately, however, there is apparently no commercial float available for hydrogen. In spite of the float's limitations, its apparent simplicity and low cost make it attractive except in applications where very high pressures are encountered.

Point Sensors

Interface detection. - All point sensors are on-off devices which locate the interface by sensing a large change in some property across it ($\Delta\chi$, fig. 12). For example the significant property for an ultrasonic switch is the product of liquid density and speed of sound ($\chi = \rho c$). The point sensor's electronics are adjusted so that the switching band $\Delta\chi_{sw}$ (that is, the change in magnitude of the significant property

required by the sensor to change its phase indication) remains within the bounds of the property change across the interface $\Delta\chi$. Since it is difficult to make $\Delta\chi_{SW}$ zero in an operation unit, interface location at high pressure could be difficult. This occurs because the interfacial property change $\Delta\chi$ gets smaller as the thermodynamic critical point is approached ($\Delta\chi \rightarrow 0$) and the bounds of χ_{SW} may fall outside of $\Delta\chi$ resulting in some possible error in interface location detection δ (fig. 12).

Sampling errors. - Point sensors, as their name implies, sample a point in space and are therefore very sensitive to sampling error (types of sampling error are discussed on pages 13 and 14). Indeed this is their main error source. It should be noted that all point sensors are about equally affected by this error source.

An ordinary stillwell can be employed to isolate the point sensor from some of the sampling errors; namely the interface wave disturbances, and reduce the potential error from this source. A schematic diagram of a possible stillwell configuration is given in figure 13. The point sensor is placed inside the stillwell, which can be described as a volume, usually cylindrical, that is hydraulically connected to the tank by some restriction. The restriction might be essentially zero, as in the case of an open pipe, or large, as in the case of small orifices with a closed pipe bottom. Orifices and a closed bottom and top (fig. 13) could be used so that bubbles and splashed droplets cannot enter inside the stillwell. An indication of the wave suppression ability of a simple open-tube stillwell as a function of immersed depth is given by figure 14. The

figure indicates that the bottom hydraulic connection of the stillwell should be as deep as possible, and that short wave length waves are the easiest to suppress. It should be noted that small orifices can also be used to suppress disturbances. However, they are difficult to analyze and can cause a level lag during a level change because they represent a large restriction to flow.

Generally it is desirable to achieve maximum disturbance suppression with a minimum level lag. An indication of the level lag error as a function of the interface velocity for various orifices and stillwell pipe dimensions is plotted in figure 15. The figure clearly shows that orifices cause far larger level lag errors than open pipes for reasonable dimensions. A long stillwell with large orifices and a closed end (the latter two are needed to block the entry of bubbles) is the desired configuration. If a short stillwell is required due to space limitations, then relatively small orifices must be used for disturbance suppression. This will cause the penalty of significant level lag with changing level.

Generally a point sensor system is used to supply liquid mass information. However, since they basically provide liquid height data, ^{the} average liquid density must be provided before liquid mass data is possible. If the bulk liquid density is sampled or provided for a non-boiling liquid, an error will occur because of liquid density gradients. The liquid mass error which occurs during a constant pressure, low heat leak, rapid outflow was 0.5 per cent or less for tank pressures not exceeding 100 psia in a small research facility. If the heat flux

is high enough so that boiling exists, then a different error will result due to the bubbles which lower the apparent density. Errors due to boiling of the order of one per cent have been measured in the same facility.

Switching time lag. - Switching time can be another major difficulty of point sensors during filling and outflow operations. Switching time is the time required for a point sensor to change its phase indication. During outflow most point sensors will exhibit very short switching times with the exception of a physically large "hot" wire. Liquid clings to this device, which must run off and/or vaporize before the gas phase can be sensed. For example, a commonly used carbon resistor "hot" wire has exhibited a 5 second switching time lag during outflow.

Another switching time problem occurs during filling when a warm sensor is immersed in the liquid. Film boiling occurs and the sensor becomes enveloped by gas. This prevents proper phase indication until the sensor cools down to nearly the liquid temperature. This cooldown time, that is the time until film boiling ceases, can be approximated for most sensors by figure 16. The figure shows that the initial and final temperatures have little effect on the cooldown time compared to the effect of the cooldown parameter $\frac{\bar{c}_m}{h} \left(\frac{W_m}{A_s} \right)$. Clearly a sensor with low weight per unit surface area $\left(\frac{W_m}{A_s} \right)$ is required for filling since $\frac{\bar{c}_m}{h}$ cannot be changed much.

The cooldown of a stillwell must also be considered because the bubbles produced inside the stillwell will cause large sampling errors. It, too, must have a low $\frac{W_m}{A_s}$. The approximate range of values of $\frac{\bar{c}_m}{h} \left(\frac{W_m}{A_s} \right)$

for a large number of commercially available sensors (ultrasonic switches, capacitive switches, optical sensors, and "hot" wires) is plotted on figure 16. Even the commercial "hot" wire point sensors have excessive cooldown times in comparison to one developed at the NASA Lewis Research Center³. The shortcoming of the commercial "hot" wires is due to the massive stillwells used in their design. NASA experience indicates that "hot" wire - stillwell systems can be designed which will cool rapidly.

Most tanks are filled through long lines which are initially warm. Therefore, a great deal of cold gas is first passed into the tank, which may partially pre-cool the level sensor and stillwell before liquid strikes it. If sufficient pre-cooling occurs, the cooldown problem will be minimized.

Practicality. - Comparison of the "hot" wire, ultrasonic and shortened and nulled continuous sensors along practical lines is again done in chart form (Table III). The reader is again cautioned that the ratings of Tables II and III are not necessarily comparable.

Miscellaneous - Temperature Rake

Little time need be consumed by a discussion of the temperature rake. It is far more costly, heavy, and complicated than other sensors considered. Most important, a "liquid level" indication cannot be easily obtained in any direct manner. The rake supplies a temperature profile

³ The author developed a "hot" wire stillwell system for hydrogen service which could be dunked, initially warm (room temperature), into a violent cryogenic fluid and still give a rapid phase change indication. This occurs because the stillwell liquid remained essentially quiet and non-boiling.

from which the liquid level can be determined as a "by-product" from knowledge of the saturation temperature. This method is only approximate because liquid superheating generally exists and normal cryogenic temperature sensors have long thermal time lags when they are moved from liquid to gas. The major application of this device should remain in research.

Applications

As a final point in the comparison of sensors, certain generalizations can be made regarding the applicability of sensors for filling, propellant utilization and zero gravity applications. The intent of this discussion will be directed toward choosing the most promising sensors for these missions.

Tank filling. - The overriding filling problem is the sensor cooldown time. Of the sensors discussed herein, only "hot" wire point sensors, and possibly the float, will cool down rapidly enough to be satisfactory for filling. Weighing is also considered since it is not affected by the cooldown problem. However, weighing for a large rocket vehicle may prove very expensive. This leaves the "hot" wire in the form of a rake with a carefully designed stillwell (it too must cool rapidly) as the apparent best choice, with the float a cheaper but more limited substitute. If fixed cost is no problem, then weighing should be considered.

Propellant utilization. - The interface-following sensors mentioned herein and the temperature rake can be immediately eliminated for practical reasons which were discussed previously. This leaves a choice between the continuous total-content sensors and the point sensors.

From the continuous sensors, the gamma radiation gage considered can be eliminated for practical reasons, as can the weighing scheme. Likewise, the bouyant force and pressure head-strain element need not be further considered mainly because they are bulky or affected by gravity forces. From the continuous-reading sensors the capacitance and the pressure head manometer type continuous sensors remain. Of the point sensors considered, the ultrasonic switch and "hot" wire appear best with the ultrasonic switch showing a slight advantage.

There is some evidence to show that a continuous sensor system can be somewhat more accurate than a point sensor system for propellant utilization. However, for now, it is probably better to report that continuous and point sensing systems are approximately competitive for propellant utilization applications.

Zero gravity. - This topic has been separated from the rest of the discussion since it is a subject of special interest by itself. It is known that at least a thin layer of liquid will cohere to an unheated sensor in a tank ^{causing it to} ~~and~~ indicate only liquid regardless of the surrounding phase. The ultrasonic switch might be excepted here since a thin film may act only as a clinging mass to its vibrating system and possibly not disrupt the required acoustic impedance different for phase indication. This exception might also hold for the "hot" wire because it could "burn off" the film of liquid as it is formed. All sensors will have great difficulty in determining the liquid mass due to the not too well defined liquid boundaries that exist at zero and near zero gravity. Point sensors

and interface followers are both far more subject to serious sampling errors under these conditions than the total-content sensors.

CONCLUDING REMARKS

A number of generalizations or conclusions can be stated from this study⁴:

1. The continuous-reading total-content sensors have essentially the same inaccuracy from their main error source considered, the mass of gas. This will be helpful in considering other sensors which fall in this class, for they too will have the same inaccuracy due to the mass of gas under the same conditions.

2. All point sensors apparently locate the interface with nearly equal accuracy, since they are essentially equally affected by sampling errors which is their main error source considered.

3. Of the sensors considered certain ones seem best suited, at this time, for particular applications. For propellant utilization, pressure head-manometer type, capacitance systems, and "hot" wire and ultrasonic switch point sensor systems are competitive. For filling, the "hot" wire point sensor seems best followed by weighing and the float in order of value. A special configuration capacitor is indicated for zero-gravity uses.

⁴ It must be remembered that this study was not aimed at analyzing sensor electronics or specific commercial products, but rather types of sensors. It is very probable that one manufacturer's product is better than another within the same class by virtue of a better design (probe and electronics). Furthermore it is possible to "design out" certain inherent faults in a particular sensor.

APPENDIX A

NOMENCLATURE

A	cross sectional area of "bob", sq ft
A_b	cross sectional area of the beam of radiation, sq ft
A_s	surface area, sq ft
A_T	cross sectional area of the tank, sq ft
B	configuration constant for the capacitor, $\mu\text{f}/\text{ft}$
C_{eff}	effective capacitance, μf
C^*	orifice coefficient
c	speed of sound, ft/sec
c_m	specific heat of the material, $\text{Btu}/(\text{lb})(^\circ\text{R})$
D_s	stillwell effective diameter, ft
D_T	tank diameter, ft
d	diameter of "bob", or orifice diameter, ft
E	output signal, volts
E'	output signal excluding the calibration contribution
E^*	modulus of elasticity, lb/sq in.
F_f	friction force, lb
f	fanning friction factor
G	a capacitor constant which depends on the fluid
g	acceleration of gravity, ft/sec
g_0	$32.2 \text{ ft}/\text{sec}^2$
h	surface coefficient of heat transfer, $\text{Btu}/\text{sq ft}(\text{hr})(^\circ\text{R})$
h	liquid level or immersion depth, ft
Δh_L	level lag, ft
h_m	liquid level of manometer fluid, ft

h_s	immersion depth of a still well, ft
I_0	intensity of radiation with no attenuation, particle/(sq ft)(sec)
i	ionization gage output, amp
K	dielectric constant
\mathcal{K} or \mathcal{K}'	transducer constant, open units
L	length of tank or sensor length, ft
M'	mechanical advantage
N	percent cooldown, $N \approx .98$
n	number of still well orifices
n'	intergers 0, 1, 2, 3, etc.
p	pressure, lb/sq in. abs
Δp	pressure difference
Q	see figure 11
$^{\circ}R$	degrees Rankine
r_f	float radius, in.
S_f	design safety factor
T_i	initial temperature, $^{\circ}R$
T_{∞}	bulk fluid temperature, $^{\circ}R$
v	interface velocity, in./sec
W_m	sensor or material weight, lb
W_c	carry weight, that part of the total float weight which is not the sphere, lb
X	an overall weight or force contribution due to pipes, embilicals, ice, snow, rain, flow, and wind, etc.
χ	significant property
χ_{sw}	significant property switching value
z	vertical component, ft

β^*	ratio of wave amplitude inside stillwell to that outside it
γ	signifies gamma radiation
δ	level error due to property gradient for point sensors
η_{fS}	error percent full scale
λ	wave length, ft
μ^*	mass scatter coefficient, sq ft/sec
μ_p	Poisson's ratio
ξ	fraction of total volume of a float submerged
ρ	mass density, slugs/cu ft
$\Delta\tau$	cooldown time for sensors, sec
$\Delta\tau^+$	ring time of sound pulse, sec

Subscripts:

CAL	evaluated at the calibrate condition
g	gas
l	liquid
m	solid material or manometer fluid
0	no attenuation

Superscripts:

-	property averaged spatially
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APPENDIX B

EQUATIONS OF OPERATION

The equations listed below describe the relation between the output signal E of a sensor and the fluid properties and amount of fluid contained in the tank. The equations are approximate and are included only for the reader's better understanding of the operating principles involved. Derivations and lengthy explanations of the equations are avoided in the interest of brevity.

Continuous Total-Content Sensors

All sensors of this class are calibrated in a tank filled with saturated vapor at atmospheric pressure.

Pressure head sensor (fig. 1)

1. Strain Element - $E' = \mathcal{K}_1 \Delta p$

$$E \approx \mathcal{K}_1 \left[\int_0^h \rho_l g \, dz + \int_h^L \rho_g g \, dz - \left(\int_0^L \rho_g g \, dz \right)_{\text{CAL}} \right]$$

2. Manometer - $E' = \mathcal{K}_2 h_m$

$$E \approx \mathcal{K}_2 \frac{1}{\rho_m} \left[\int_0^h \rho_l \, dz + \int_h^L \rho_g \, dz - \left(\int_0^L \rho_g \, dz \right)_{\text{CAL}} \right]$$

Capacitance sensor (fig. 2) -

$$E' = \mathcal{K}_3 C_{\text{eff}} = \mathcal{K}_3 B \left[\int_0^h K_l \, dz + \int_h^L K_g \, dz \right]$$

$$E \approx 3B\mathcal{K}_3 \left[\int_0^h \frac{G\rho_l}{1 - G\rho_l} \, dz + \int_h^L G\rho_g \, dz - \left(\int_0^L G\rho_g \, dz \right)_{\text{CAL}} \right]$$

for hydrogen:

$$\frac{G\rho_l}{1 - G\rho_l} \approx G\rho_l$$

Bouyant force sensor (fig. 3) -

$$E \approx K_4 M' \left[\int_0^h A \rho_l g \, dz + \int_h^L A \rho_g g \, dz - \left(\int_0^L A \rho_g g \, dz \right)_{\text{CAL}} \right]$$

Weighing (fig. 4) -

$$E \approx K_5 M' \left[\int_0^h A_T \rho_l g \, dz + \int_h^L A_T \rho_g g \, dz - \left(\int_0^L A_T \rho_g g \, dz \right)_{\text{CAL}} + (X - X_{\text{CAL}}) \right]$$

Radiation sensor (fig. 5) -

$$E' \propto i; \quad i = K_6 A_b I_0 \exp \int \mu^* \rho \, dz$$

$$E \approx K_6 \left[\ln \frac{i}{i_0} - \ln \frac{i_{\text{CAL}}}{i_{0,\text{CAL}}} \right] \approx K_6 \mu^* \left[\int_0^h \rho_l \, dz + \int_h^L \rho_g \, dz - \left(\int_0^L \rho_g \, dz \right)_{\text{CAL}} \right]$$

Continuous-Interface Followers

Float (fig. 6)

$$E \propto h$$

Sonar (fig. 7)

$$E' \propto h$$

$$E = K_7 \left(\frac{h_{\text{CAL}}}{\Delta \tau_{\text{CAL}}^+} \right) \Delta \tau^+$$

Point Sensors

Ultrasonic switch (fig. 8)

$$\Delta E)_{\text{across interface}} \propto [(\rho c)_g - (\rho c)_l]$$

Hot wire (fig. 9)

$$\Delta E)_{\text{across interface}} \propto \left[\frac{1}{M_g} - \frac{1}{M_l} \right]$$

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1. Friedman, J., DeBoHari, L.: Which System for Propellant Level Sensing? Aerospace Engineering, Aug. 1960.
2. Scott, R. V.: Cryogenic Engineering. Van Nostrand Co., 1950.
3. Storage, Transfer and Servicing Equipment for Liquid Hydrogen. A. D. Little, Inc., WADC TR 59-386, July 1959.
4. Investigation of Full Quantity Measuring Techniques. Raytheon, Contract No. AF 33(038) 22632, ATI 166433.

TABLE I. - RELATIVE EFFECT OF SAMPLING ERRORS

Item number	Sensor Type of sampling error	Pressure head	Capacitance	Bouyant force	Radiation	Legend:
		1	2	3	4	A - Small effect C - Intermediate effect D - Large effect F - Not recommended
1	Interfacial waves (no additional wave suppression)	C	A	D	D	Remarks The normally used coaxial capacitor provides its own stillwell. Surface disturbances are attenuated with depth thereby assisting the pressure head sensor.
2	Vertical density gradients	A	A	A	A	All the sensors average the density gradient locally in the vertical direction.
3	Radial density gradients	C	C	C	C	Approximately equally affected.
4	Spatially nonuniform boiling	A	D	D	A	Sensors 2 and 3 represent a heat source (storage and/or path) for nonuniform boiling.
5	Uniform boiling	C	C	C	C	Approximately equally affected.
6	Splashing	A	C	C	A	Splashed fluid can wet sensors 2 and 3.
7	Sensor distortion	A	D	D	A	Only the significant vertical dimension of sensors 1 and 4 can be affected.
8	Tank distortion	A	A	A	A	Approximately equally affected

TABLE II. - PRACTICALITY OF CONTINUOUS READING TOTAL CONTENT
SENSORS FOR SERVICE IN LIQUID HYDROGEN

Item number	Sensor type	Pressure head manometer	Pressure head strain element	Capacitance	Bouyant force	Weighing	Radiation	Legend: A - Clearly superior C - Intermediate value D - Clearly inferior F - Not recommended ? - Not enough information
		1	2	3	4	5	6	Remarks
1	State-of-the-art	A	A	A	A	A	F	The radiation gage has not been successfully developed for LH ₂ in spite of large effort.
2	Weight of system	A	A	C	C	D	?	Sensor 5 is necessarily large.
3	Inherent electrical problems	A	C	C	A	A	?	Sensor 3 has major difficulties with stray capacitance
4	Effect of fluid contamination	A	A	D	A	A	A	Contamination could affect a capacitor markedly
5	Ease of servicing and check-out	A	A	C	C	A	A	Sensors have active elements external to the tank
6	Shaping	C	C	A	A	C	C	"A" sensors can be mechanically shaped to compensate for tank shape
7	Safety to personnel	A	A	A	A	A	?	A license is needed to operate sensor 6
8	Direct effect of flow on reading	D	D	A	D	C	A	Sensors 1, 2, 4, and 5 require a careful design for accurate sensing during flow operation
9	Effect of vibration on reading	A	C	A	D	D	A	Sensors 2, 4, and 5 are weight systems and therefore subject to vibration
10	Flexibility of missions	A	C	A	D	D	D	Sensors 4 and 5 can only be used in static situations, while item 6 is not developed
11	Filling applicability	D	D	D	D	A	A	Sensors 1 to 4 would require prior gas cooldown
12	Flight applicability	A	C	C	F	F	?	Sensors 4 and 5 are clearly for ground use. Item 2 needs accelerometer

TABLE III. - PRACTICABILITY OF POINT SENSORS FOR LIQUID HYDROGEN SERVICE

Item number	Sensor type	Mulled continuous sensor	Shortened continuous sensor (capacitor)	Ultra-sonic	Presently available commercial "hot" wire	Legend:
	Item	1	2	3	4	A - Clearly superior C - Intermediate value D - Clearly inferior F - Not recommended ? - Not enough information
1	State-of-the-art	?	A	A	A	The state-of-the-art of sensor 3 varies with the manufacturer.
2	Weight of sensor	D	C	C	A	Sensor 1 is much heavier
3	Inherent electrical complexity	C	C	C	A	
4	Effect of fluid contamination	?	C	A	A	If sensor 1 is a capacitor it gets a "C" rating.
5	Ease of servicing and checkout	?	A	A	A	If sensor 1 is a capacitor it gets a "C" rating.
6	Shaping	?	C	C	C	Sensors 2, 3, and 4 must take tank shape into account electrically.
7	Safety to personnel	A	A	A	A	If sensor 1 is a radiation gage it gets a "?" rating.
8	Direct effect of flow on reading	?	A	A	A	See this item on table II for more data on sensor 1.
9	Effect of vibration on reading	?	A	C	A	See this item on table II for more data on sensor 1. Sensor 3 is a vibrating system.
10	Flexibility of missions	A	C	C	C	Sensor 1 merely requires electrical adjustment for different levels.
11	Filling applicability	F	F	F	A	Only the "hot" wire will cool down fast enough if properly designed.
12	Flight applicability	C	C	A	C	The state-of-the-art for sensor 3 in this area is generally good.

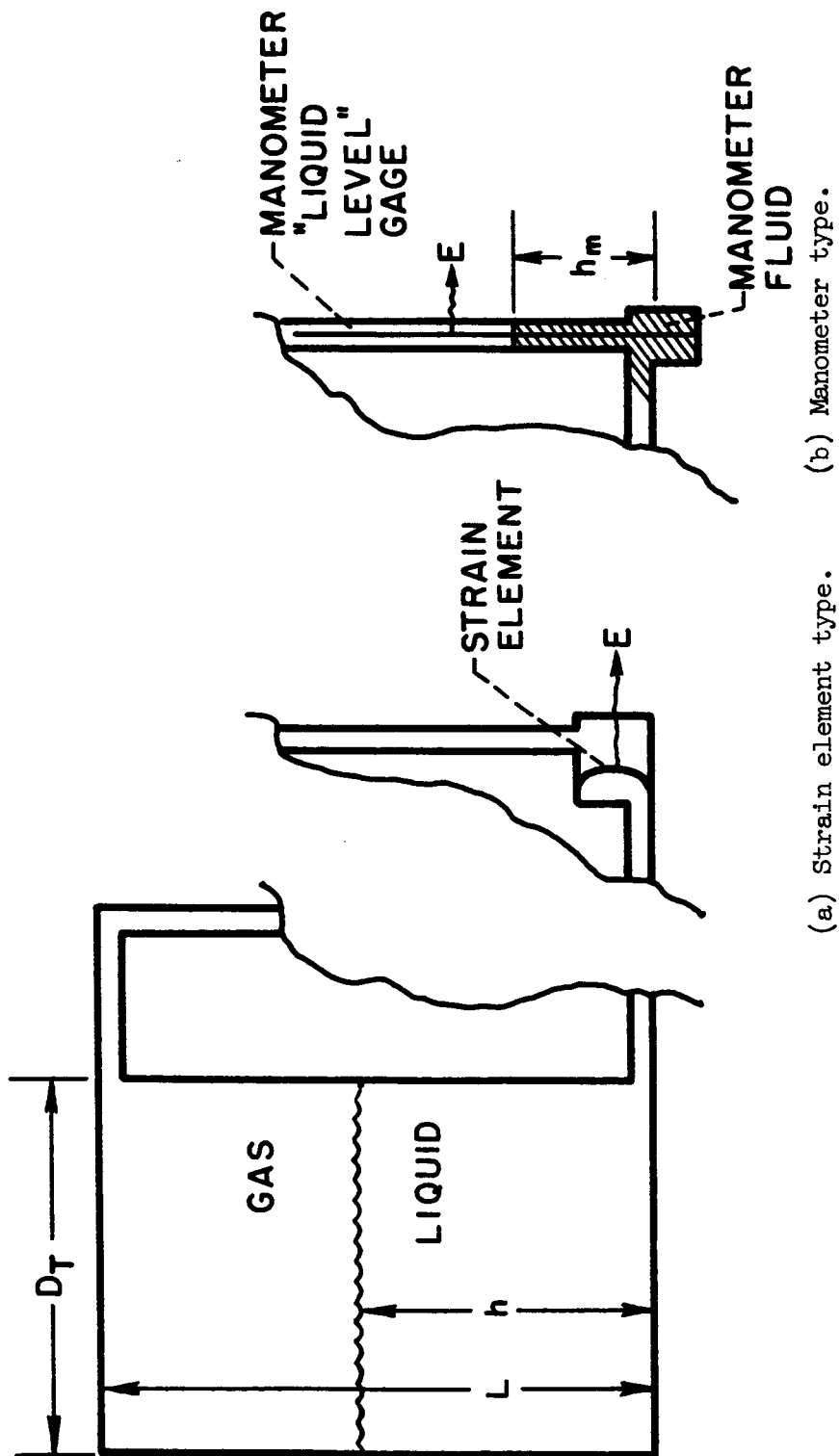


Figure 1. - Schematic of a pressure head liquid level gage.

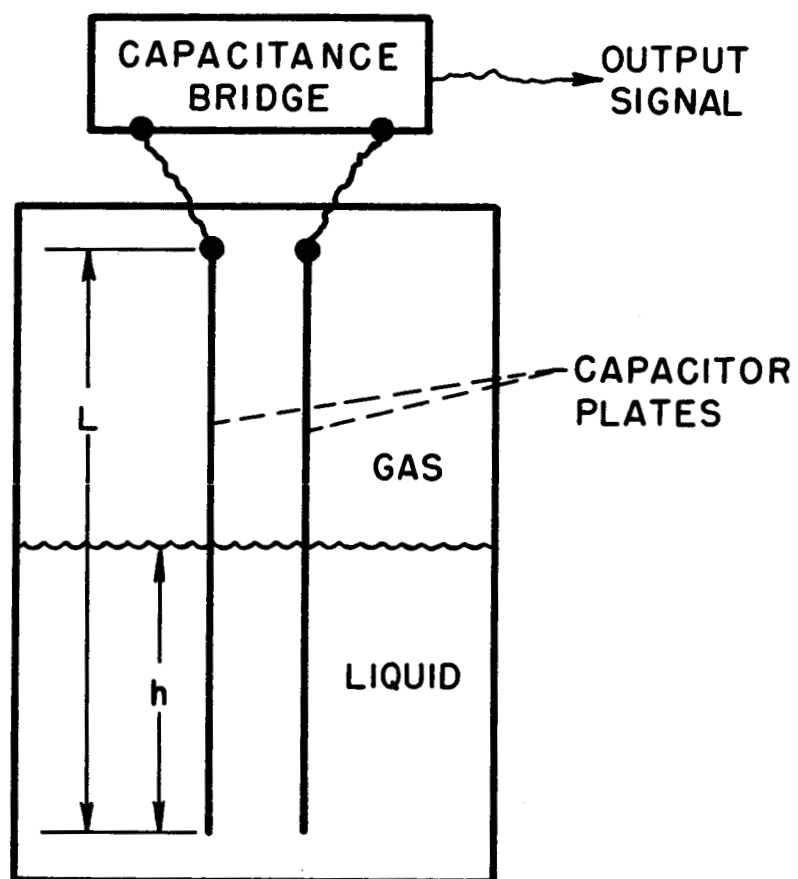


Figure 2. - Schematic of a capacitance liquid level gage.

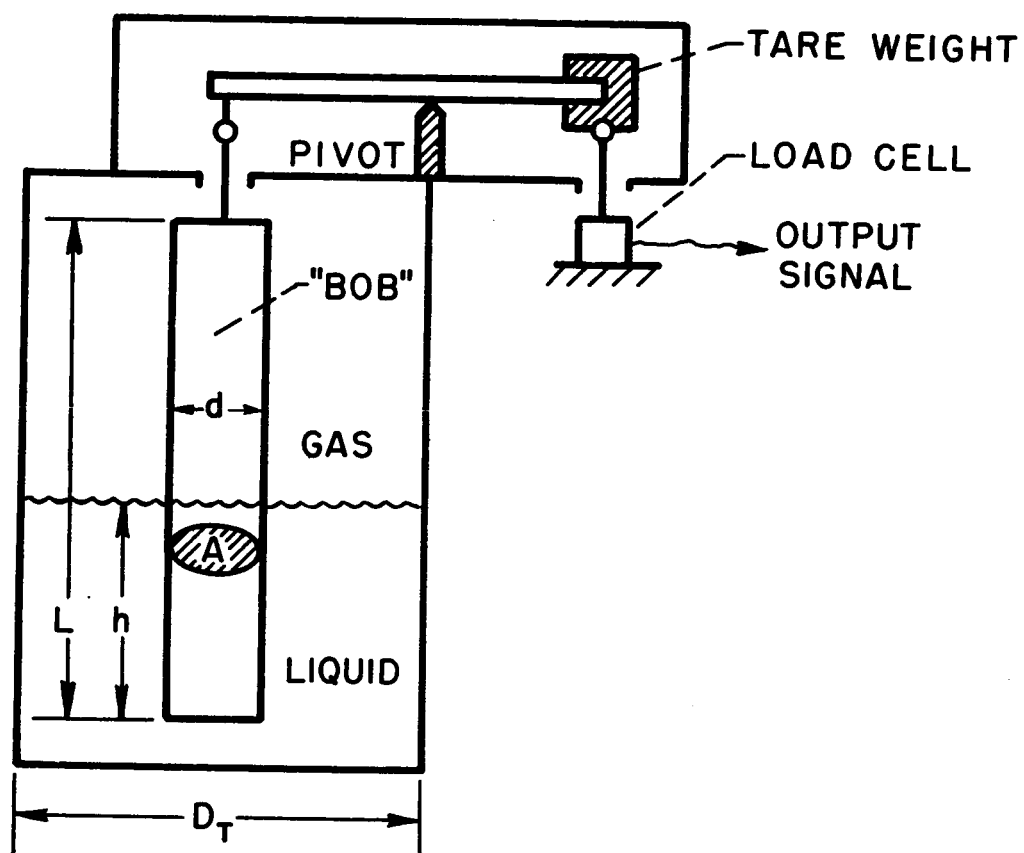


Figure 3. - Schematic of a bouyant force liquid level gage.

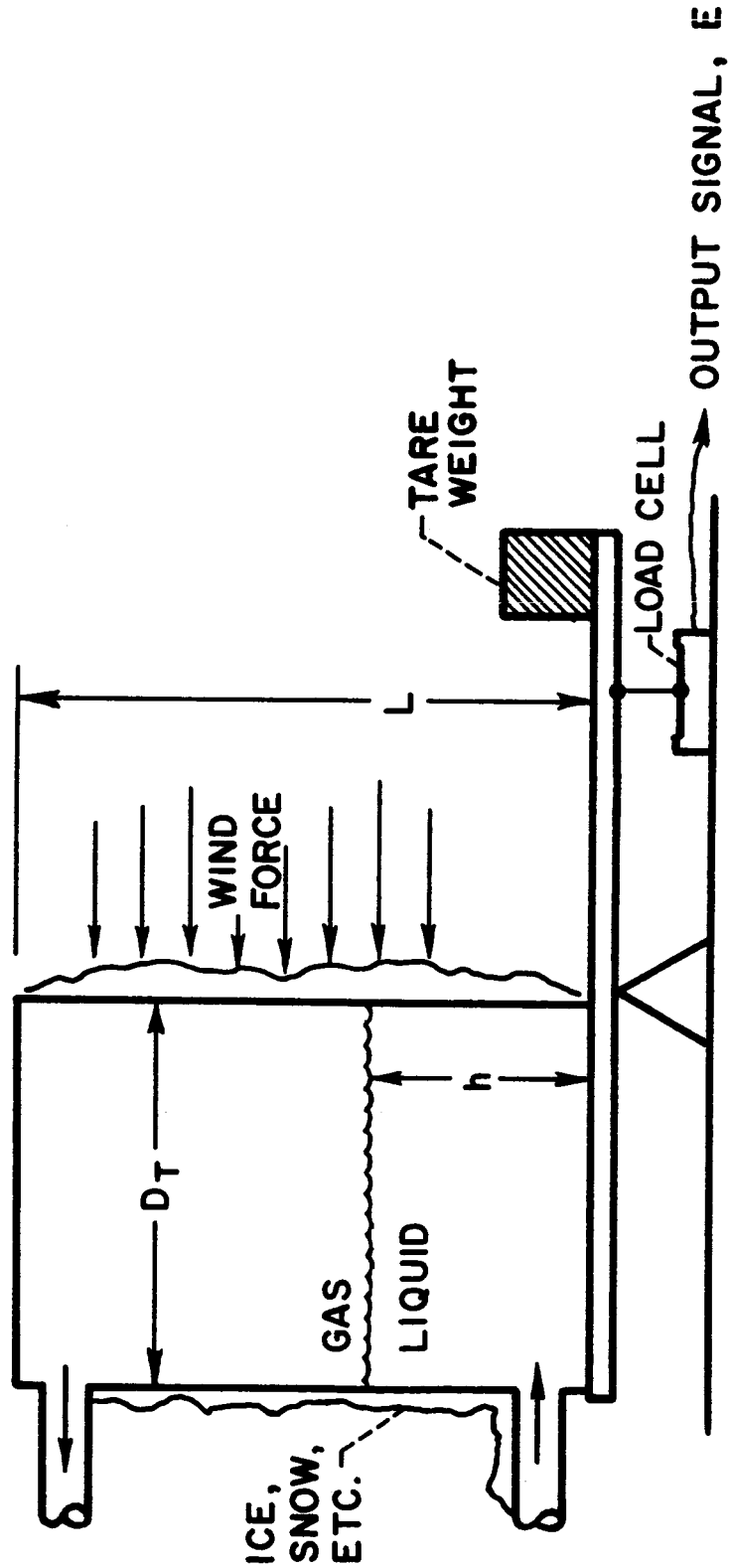


Figure 4. - Schematic of a weighing scheme.

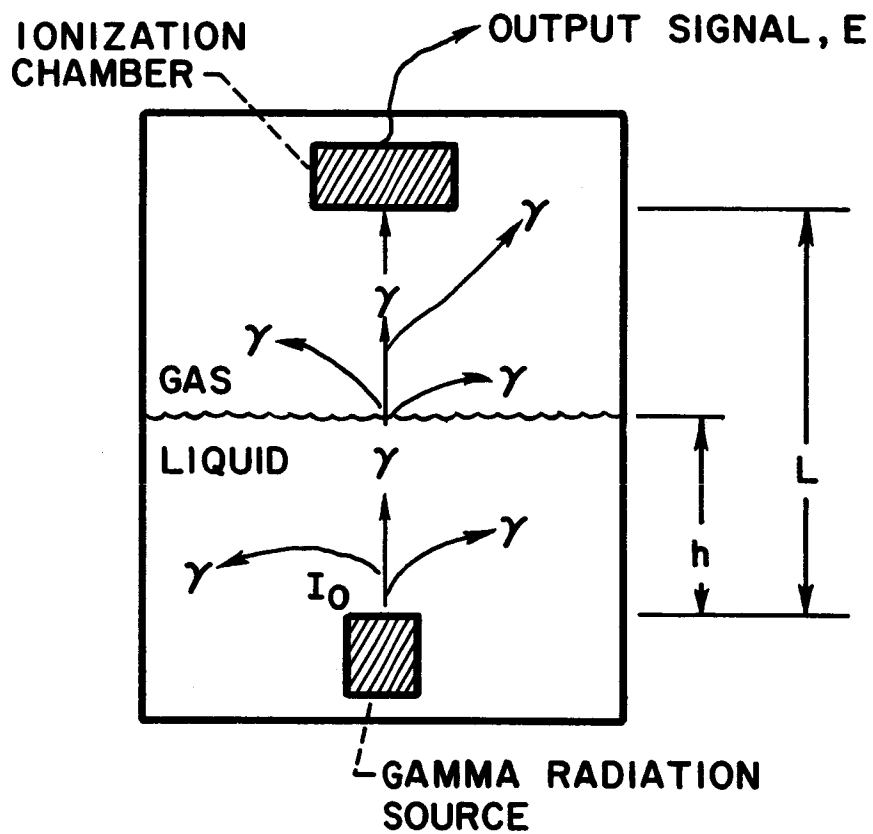


Figure 5. - Schematic of gamma radiation liquid level gage.

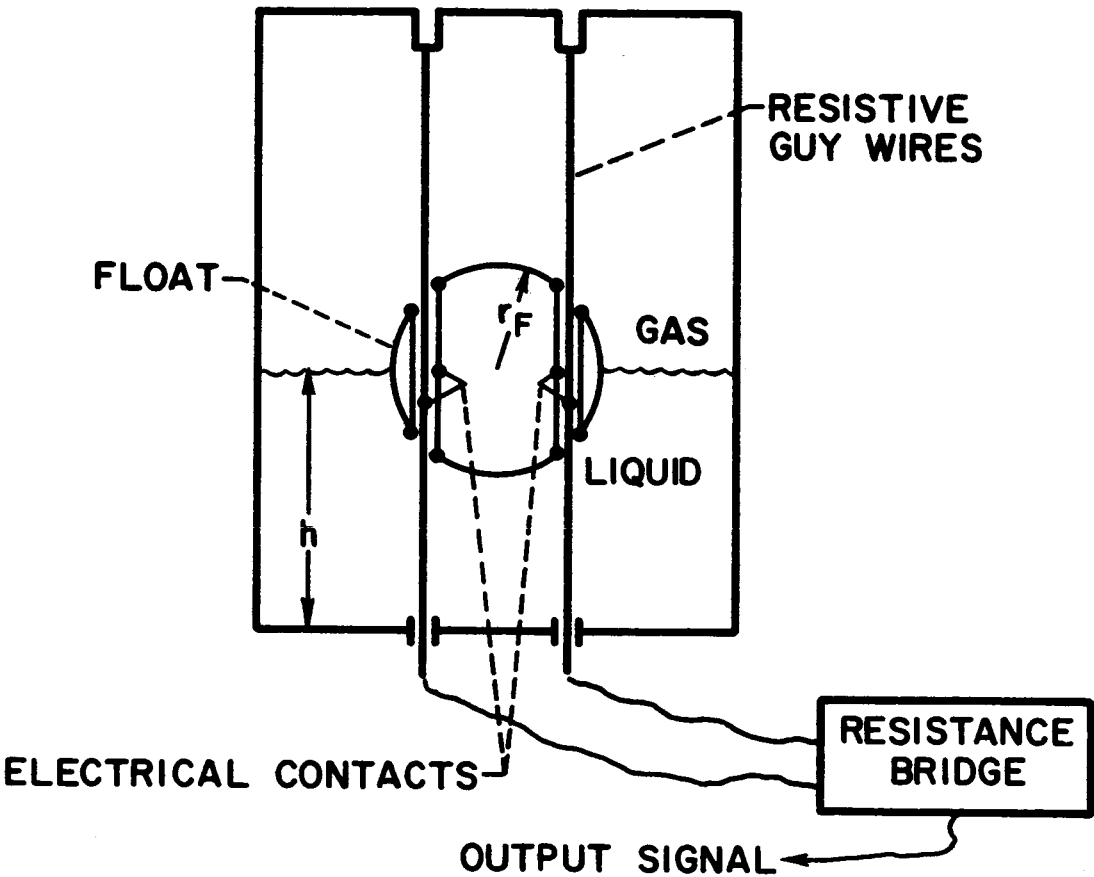


Figure 6. - Schematic of float liquid level gage.

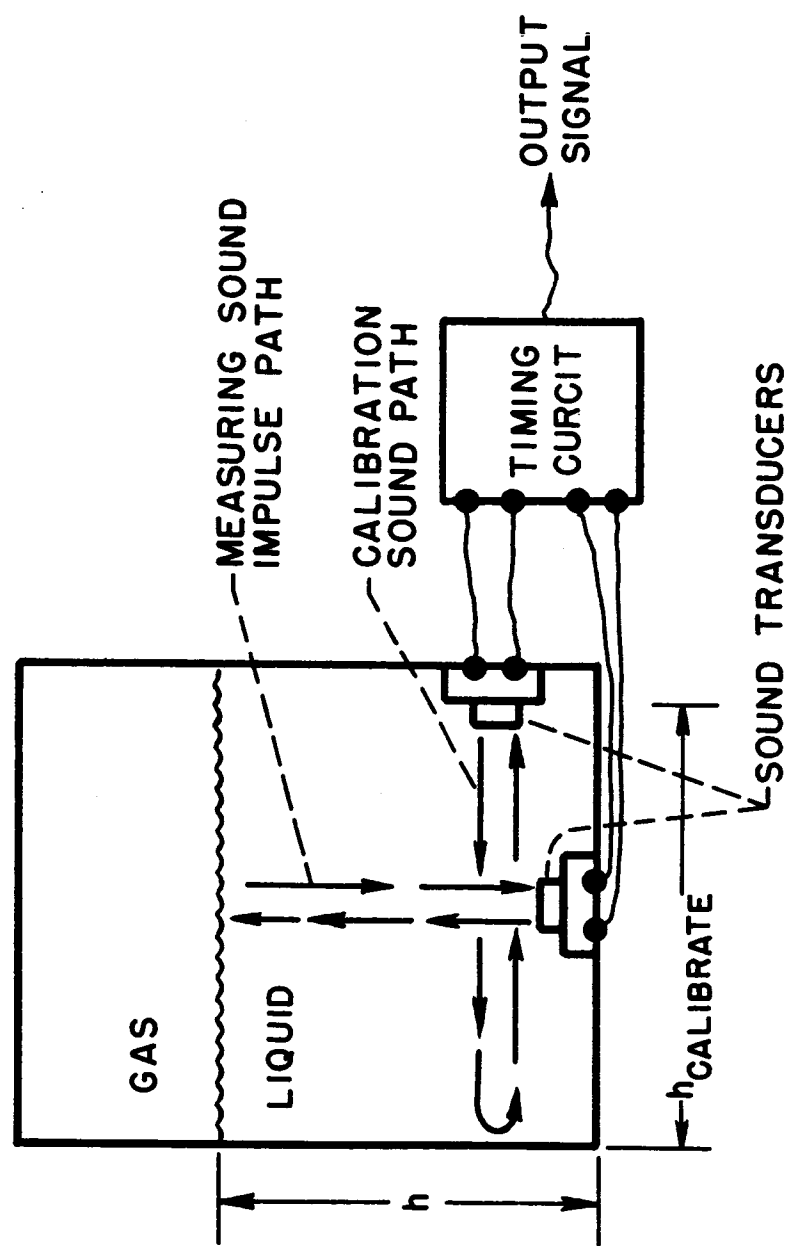


Figure 7. - Schematic of sonar liquid level gage.

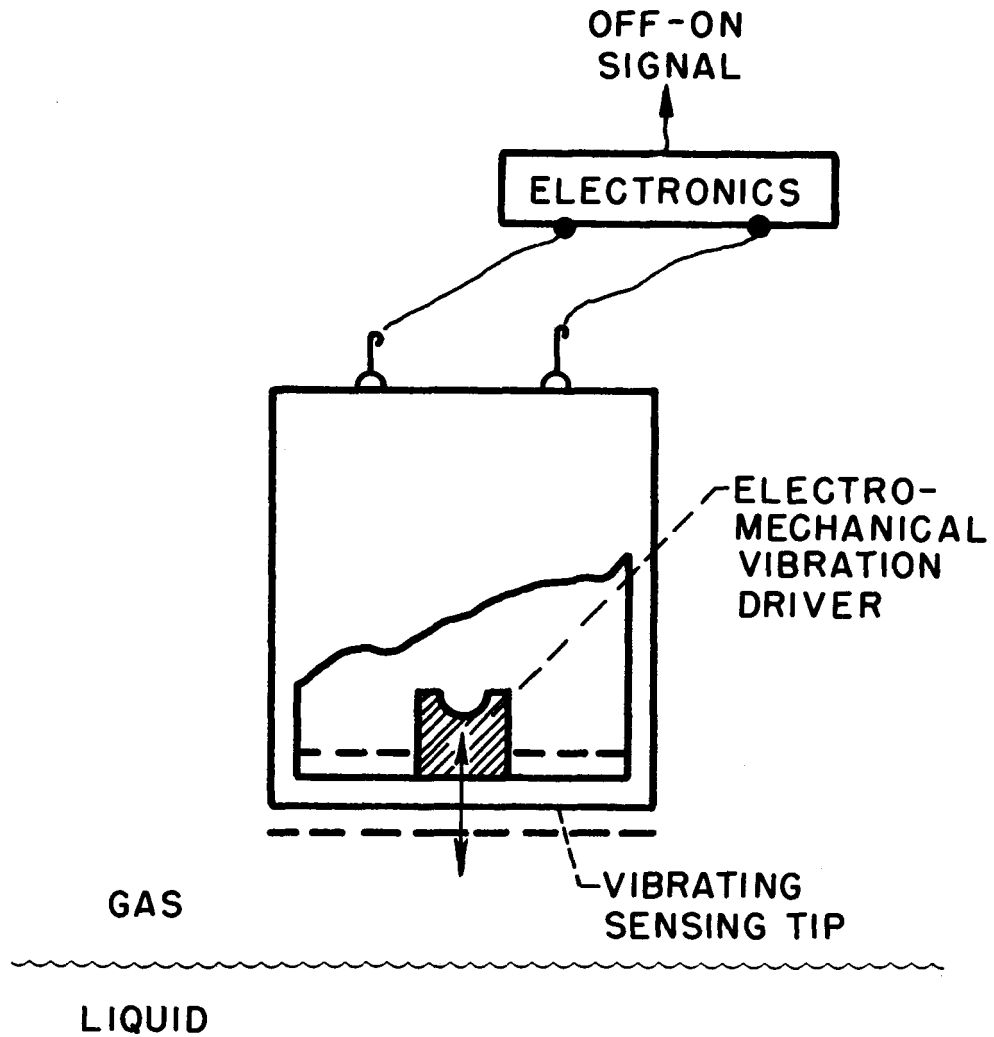


Figure 8. - Schematic of an ultrasonic switch.

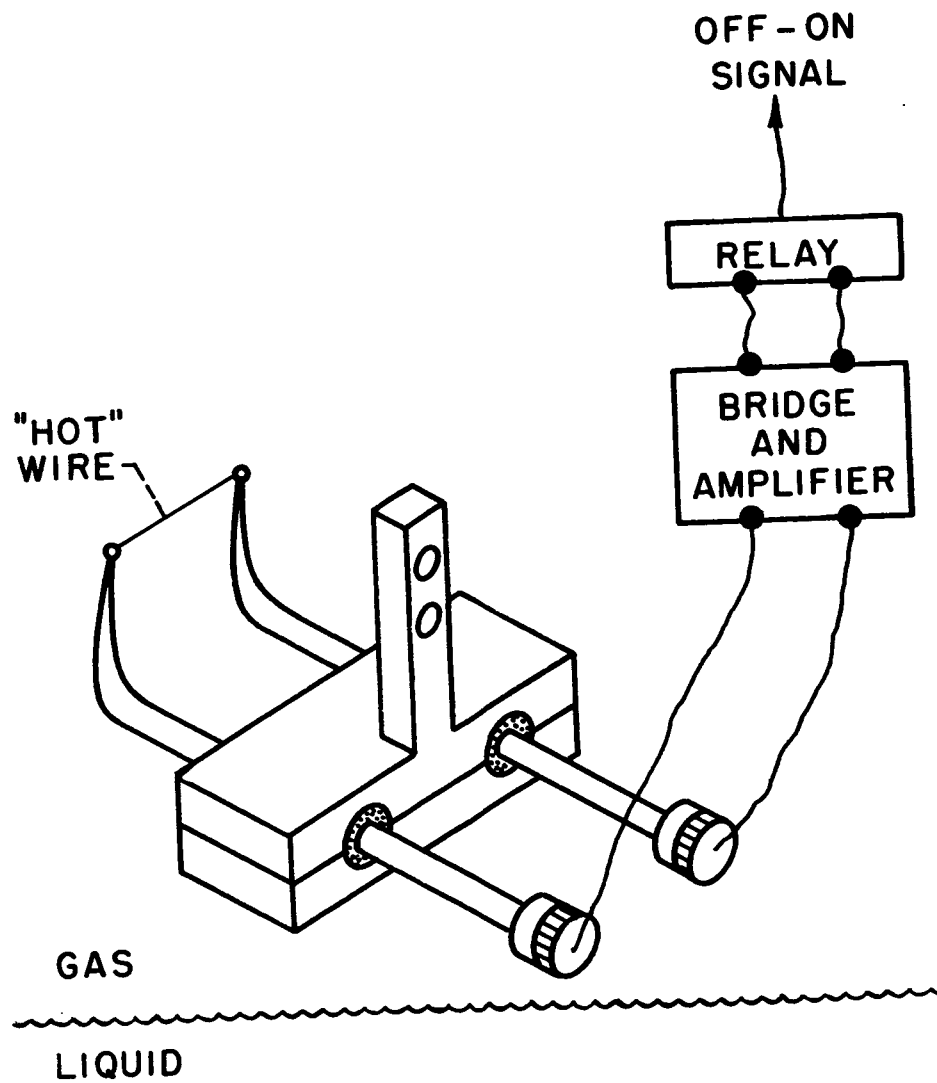


Figure 9. - Schematic of a hot wire point sensor.

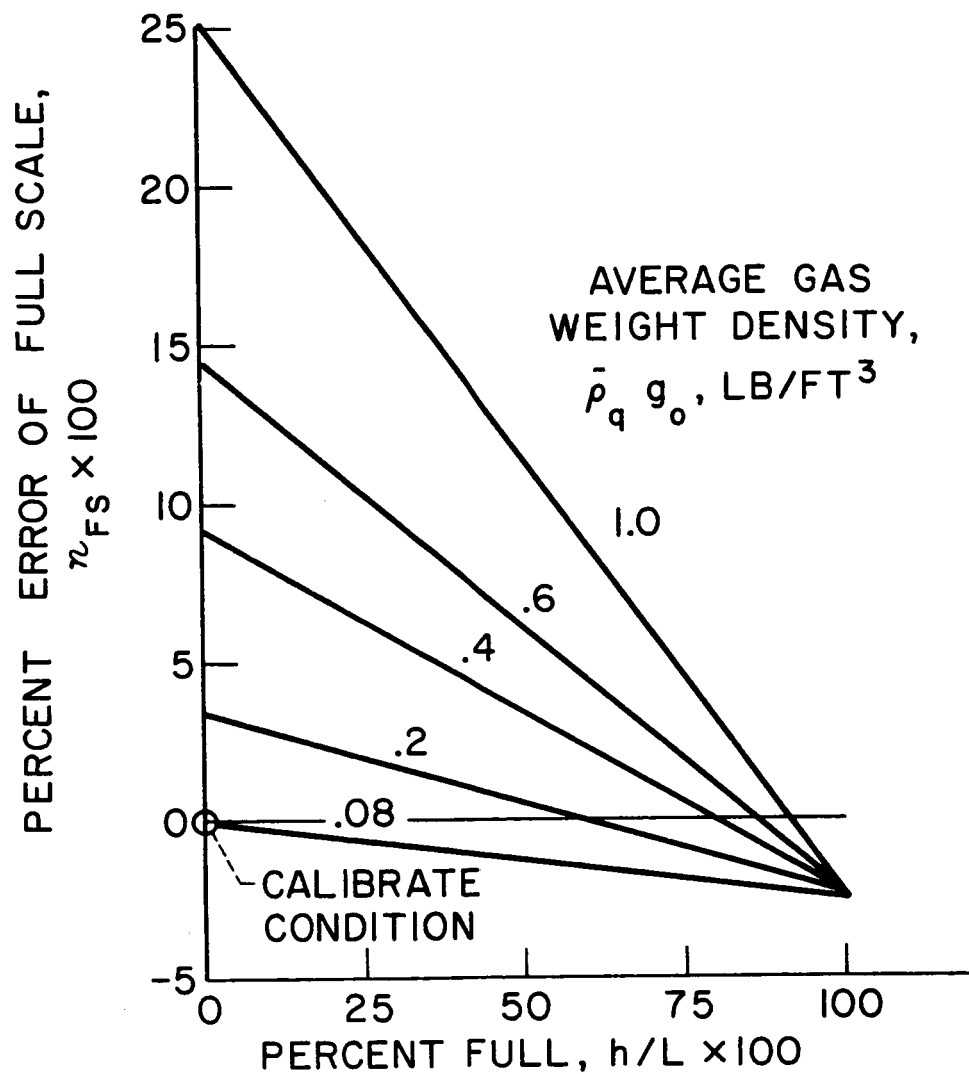


Figure 10. - Approximate error in liquid mass determination for continuous total content sensors in hydrogen due to the mass of gas.

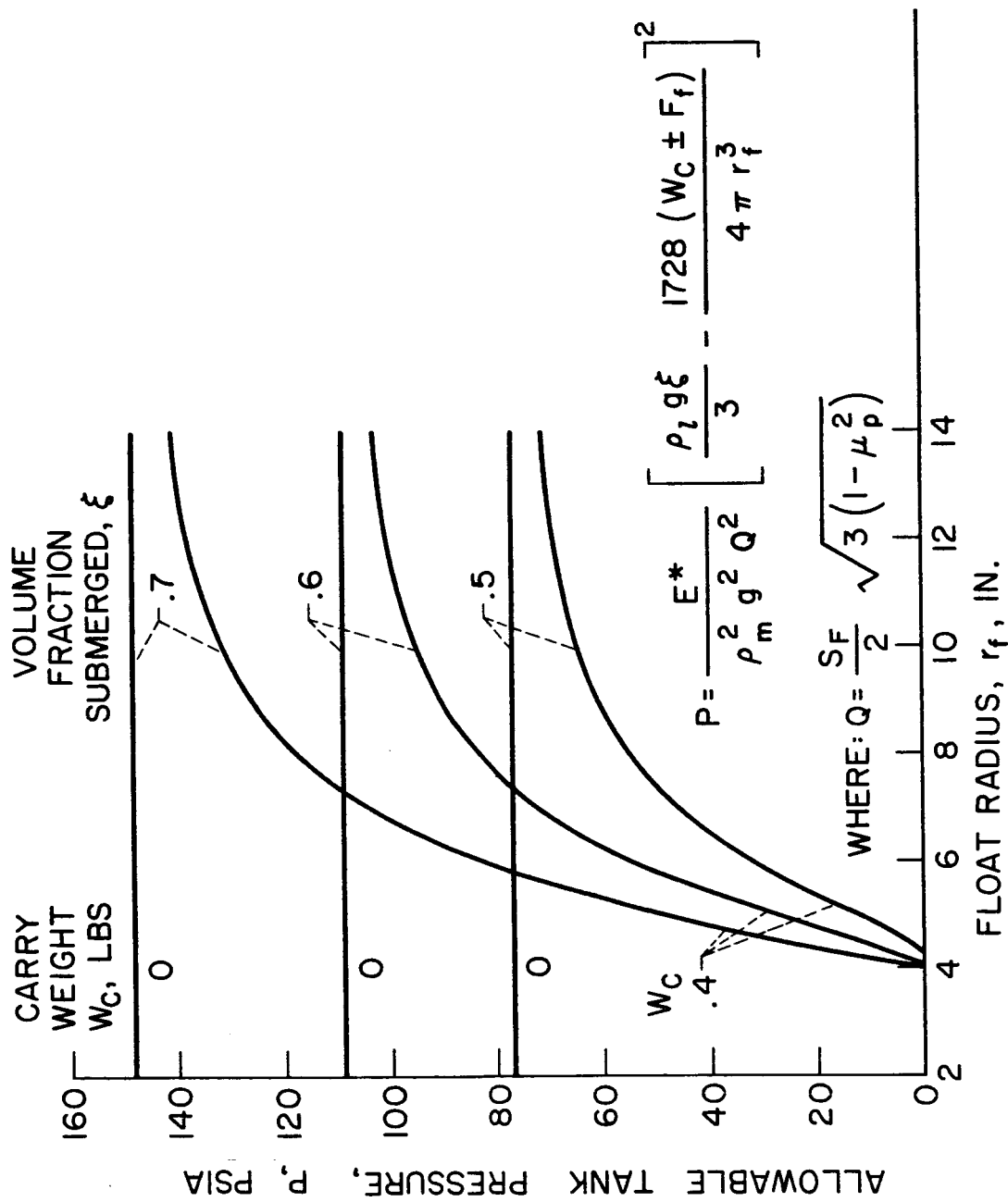


Figure 11. - Allowable pressure for an aluminum sphere floating in hydrogen ($S_F = 3$, $F_F = 0$).

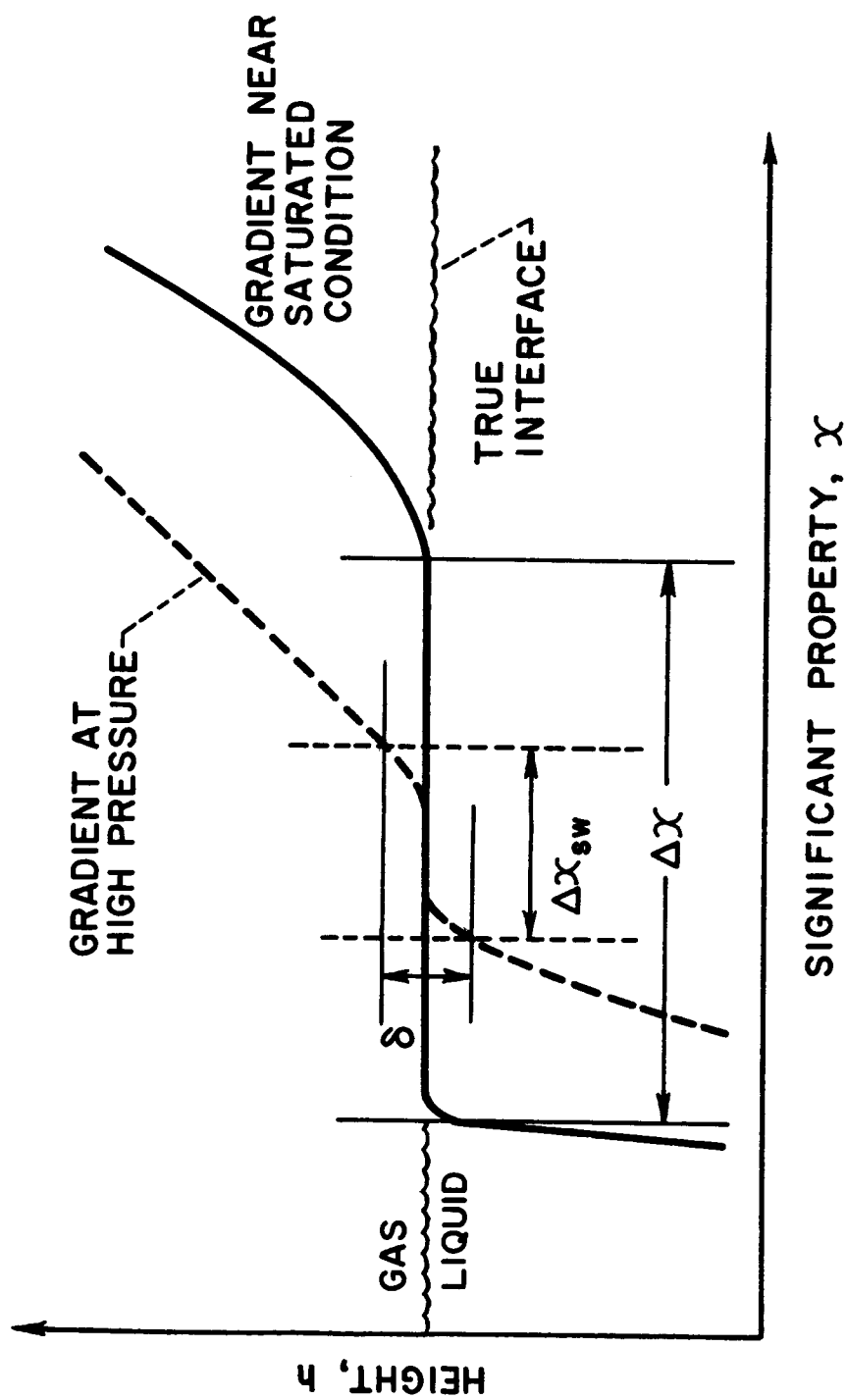


Figure 12. - Typical property gradient across the interface.

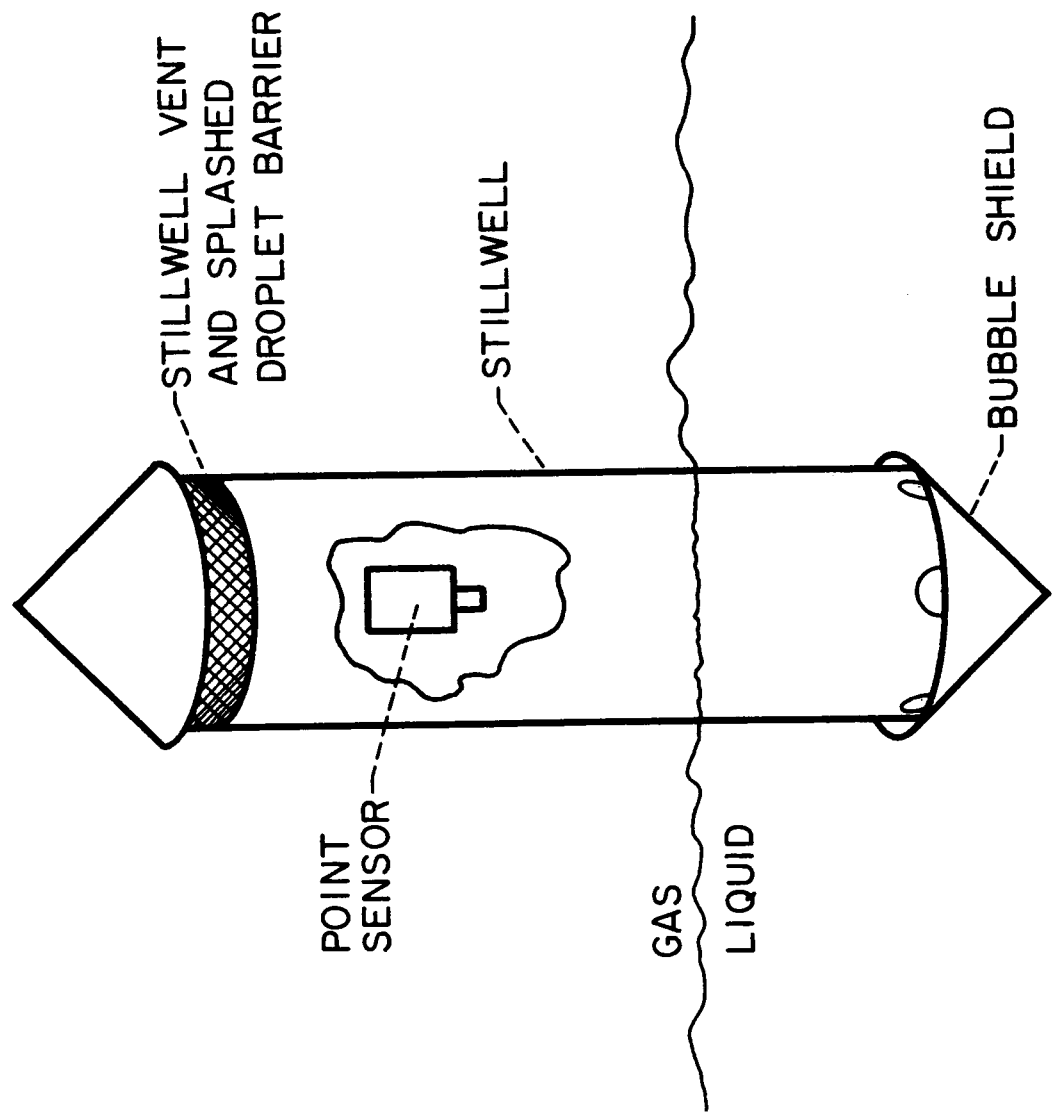


Figure 13. - Schematic of a stillwell for point sensors (closed bottom with orifices).

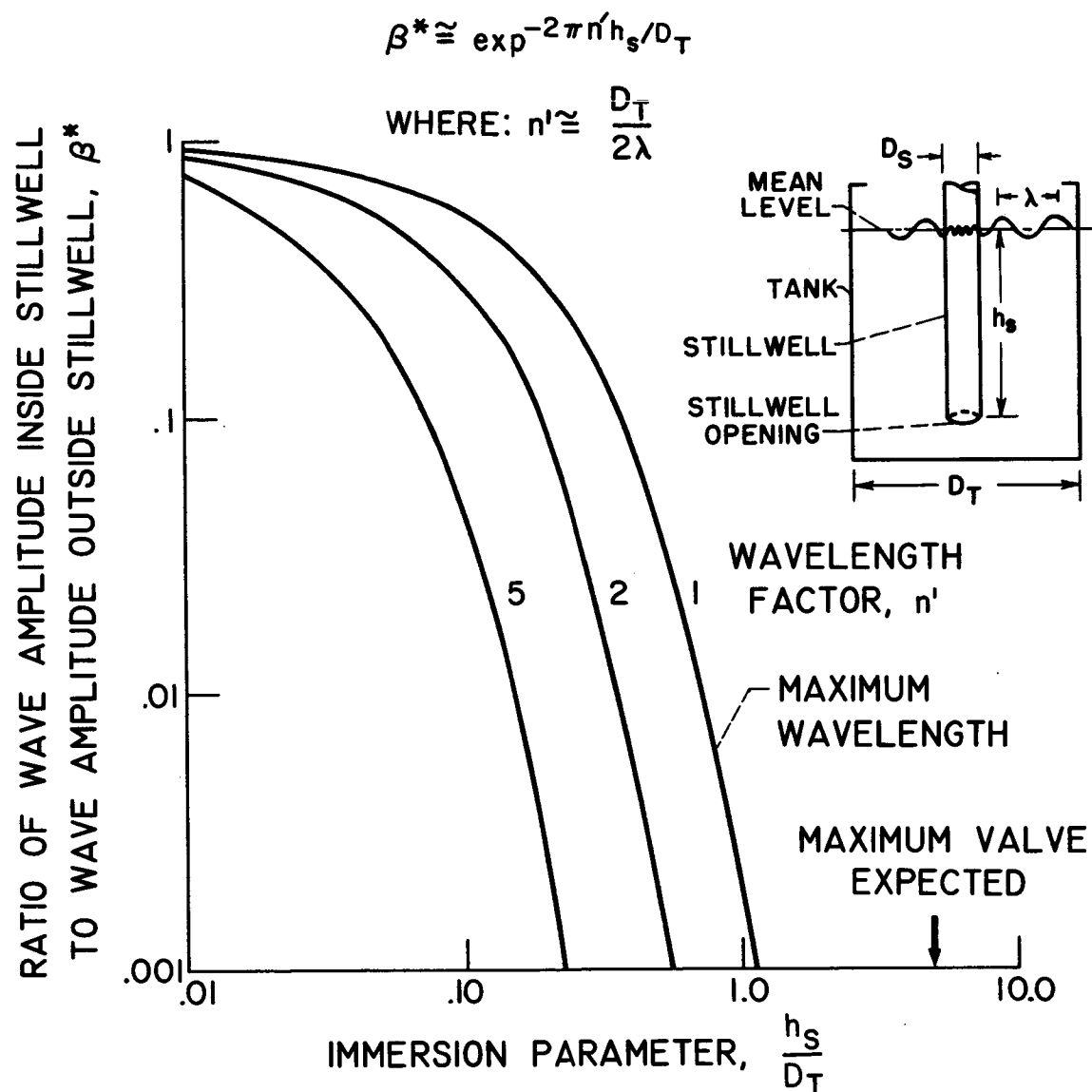


Figure 14. - Stillwell disturbance suppression vs immersion parameter.

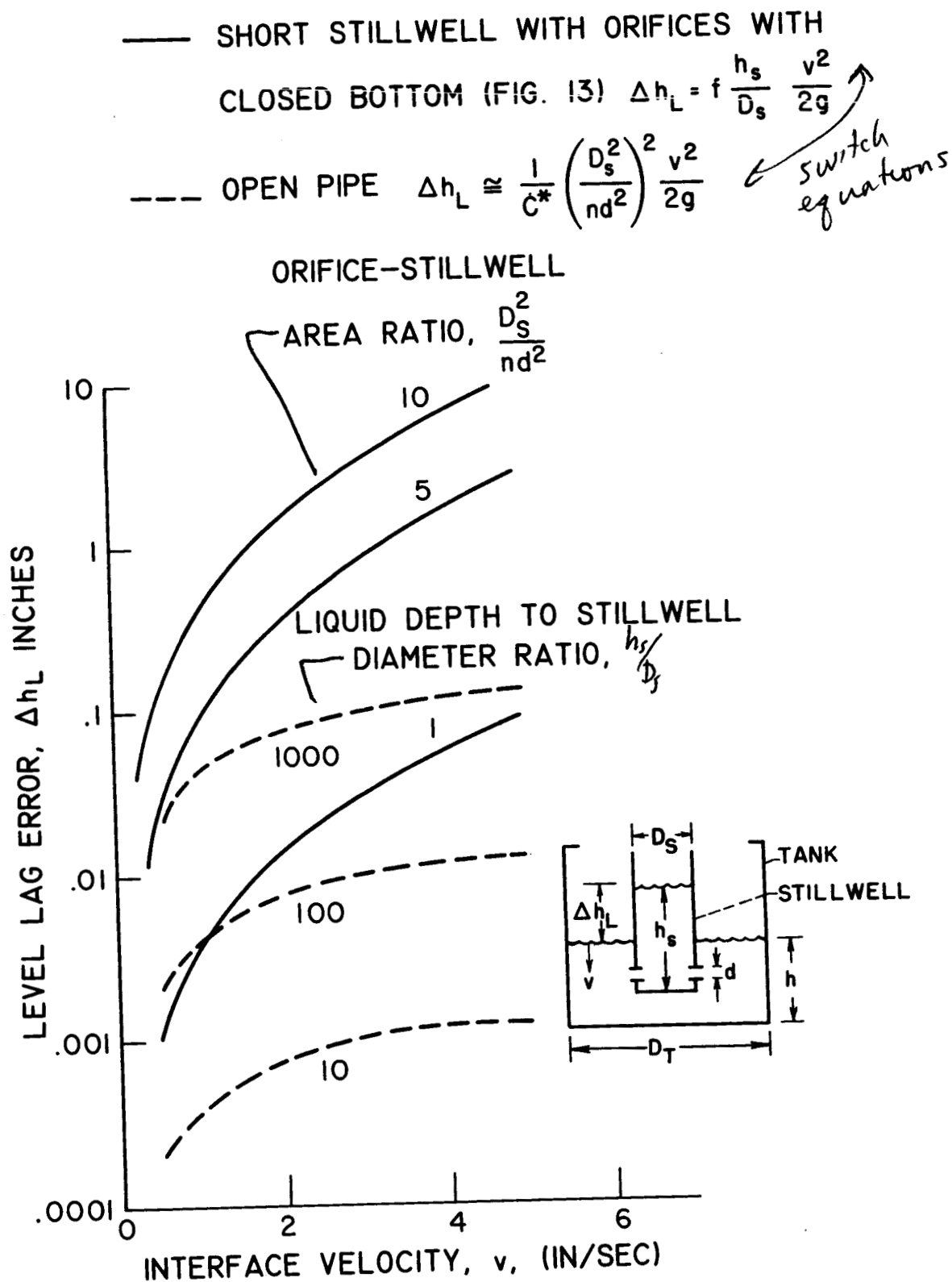


Figure 15. - Level lag for Stillwell.

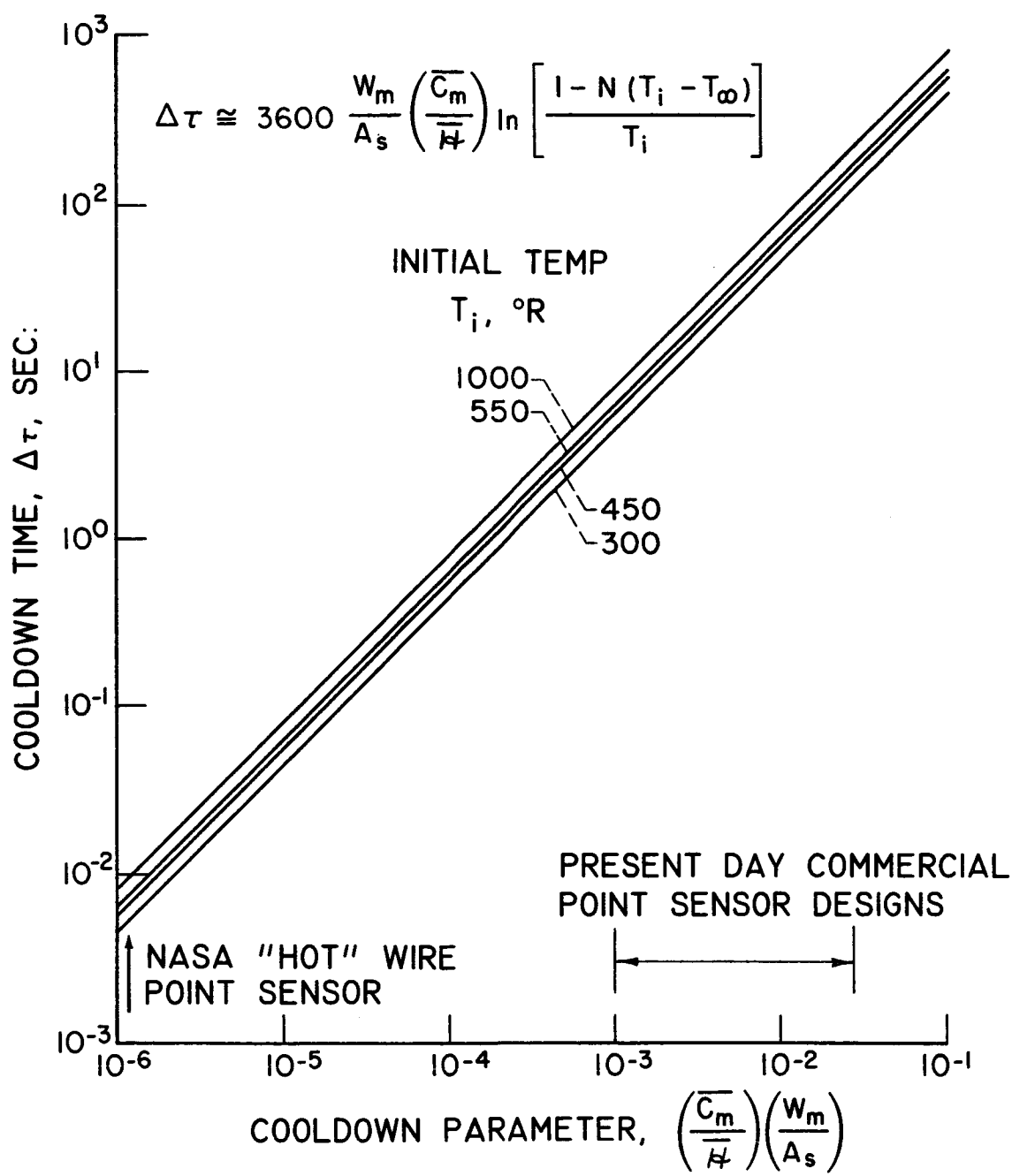


Figure 16. - Sensor cooldown time in liquid hydrogen. The sensor, initially at T_i , is rapidly immersed in liquid hydrogen at $36.7^\circ R$. $h, \bar{C}_m = \text{const}$, no heat generation.